Spatial risks and complex systems :methodological perspectives

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Abstract: The reflections regarding risk and industrial catastrophes question the complexity theories. Besides the new concepts which lead us to question older concepts (risk, hazard and vulnerability), we propose to think about more practical aspects, for example the modelling of human behaviour and the confrontation in crisis situations. The link between concepts as: critical self-organization, emergence, bifurcation, and the methods in the Distributed Artificial Intelligence used to model them is however difficult. In this paper, we present ongoing analysis on the key concepts of risk science, such as the hazards and the catastrophes. We propose to enrich them with complex systems theories. First, we present methodological perspectives of the DAI, for example multi-agent systems, and compare them with other simulation methods used in the context of the risks. Secondly, we present the MOSAIIC model (Modelling and Simulation of Industrial Accidents by Individual-Based methods) which gives possibilities to simulate the behaviour of individuals during an industrial accident. The project and the MOSAIIC model aim to explore the effects of a major industrial accident on public health. For instance, the emission and the spread of a toxic gas in an urban environment may be a serious danger for the human health. Thus we propose to study the consequences of this type of event in order to reduce the vulnerability of the populations. In the model, we emphasize both on spatial and behavioral dimensions (ie.

mobility and perception of risk) All these questions lead us to use different methodologies of analysis. For example, concerning mobility, the daily traffic can be simulated at a meso scale: a road axis for example. In that way, we aim to simulate the global dynamics of the network from the modelling of flows on arcs of the network (modulated according to the time of day and the day of week). Yet, we use classical models (for instance equilibrium models) because they give an "average image" of the flows of vehicles on the arcs. Based on this first structural mobility, it is then possible to consider "a change of level" regarding both the representation and the analysis: if a risk occurs or if a specific context disrupts the structure. As a consequence, from a management of flows on the arc, we turn to an analysis of the individual behaviours in a multi-agent system.

1 Introduction

We considered risks and hazards from the point of view of complexity, and especially through the theory of self-organization and critical behaviour. Our case of study is the diffusion of a toxic cloud caused by the explosion of an industrial plant and its spread in an urban area. The aim of this research is to study, through modelling, the consequences of this kind of events on the population and especially on their mobility behaviours, in order to reduce the vulnerability of networks. If some models, such as fluid dynamics, seem to be efficient to handle the structural traffic in a network, they seem to be less useful if we aim to model a disrupted situation. Agent-based models offer a solution. They allow, during the time of the event, to switch from a management of flows at the level of arc, i.e. the road of a network, to a formalization of behaviours at the level of the individual. This methodology is more appropriated to deal with different situations, and especially for the analysis of panic for which nonlinear dynamics are important. Nonlinear means that very small variation on the model parameters (for example, the number of population susceptible to panic) have significant effects on the evolution of the system (from non-panic to collective panic), which is qualified as a bifurcation. In this paper, we will first go back over the concepts of the science of risks, such as hazard and disasters, that we will reformulate and enrich through the theory of complex systems. Second, we will present briefly the MOSAIIC project designed to simulate the behaviour of individuals facing an industrial accident.

2 Risks and complexities

Hazard and vulnerability are two concepts mobilized to define the risk. After delimiting them briefly, we will question them in relation to the theories of complexity, especially that of self-organized criticality [1].

2.1 The risk, a compound of hazard and vulnerability

Natural, societal or technological risks (R) are essentially tackled through two key concepts: hazard (A) and vulnerability (V). The risk is a measure crossing hazard and vulnerability according to a function $R = f(A, V)$. In this acceptance, and as A. Dauphiné emphasizes [2] it, a disaster is a reality whereas a risk is a probability. Hazard is generally defined both as a probability to occur and as an intensity. Regarding environmental risks, hazard is a measure which results from the probabilities observed on a long time scale. On the contrary, regarding technological risks, the probability to occur is less relevant because of the infrequency of these risks and of the theoretical absence of another occurrence in the future, except if we consider a natural cycle of Human mistake. In order to put off this limit, one tries to find the conditions liable to trigger a harmful event for people and equipments. An event tree analysis can be implemented to identify these causes and effect sequences as well as to determine theoretical probabilities. The intensity of the phenomena is the second dimension of hazard. It depends on the duration of this phenomena and of the considered area. This intensity is often employed to define the areas of protection surrounding industrial sites for example. The probability to occur and the intensity are thus the two key elements of studies which deal with hazard, but both of them become significant if the stakes, also called here the targets, have an interest recognised by a society at a particular time. This leads us to the second concept linked with risks: the vulnerability. Vulnerability generally expresses both the measure of a damage to equipments and people and the ability of a society to resist a disaster. The determination of the vulnerability at a global level thus depends on the stakes exposed to a hazard and on factors of vulnerability (sensitivity of population, resistance of houses and premises, but also the quality of risk prevention, the management of disasters with supervision and alarm systems). So, the identification of the stakes potentially important for the system in question is needed: people for an epidemic, buildings and population for an earthquake, biological factors for an oil slick...However, the existence of domino effects add difficulties to analyse the stakes. For instance, an earthquake destroying buildings may also cause victims among their inhabitants and may provoke an industrial accident whose consequences may be the flow of toxic products in a nearby river. These multi-risk scenarios are feared, especially in countries like Japan. In order to take into account this complexity, we can either use synthetic indicators based on qualitative studies or model and simulate the dynamics of such systems [3].

2.2 Complexity, bifurcation and resilience

In order to integrate the theories of complexity in the study of risks, we have to face a major challenge: that of time of processes and their interactions.

Following the above concepts, risk is defined as a probability of spatial interaction between sources and targets. From this definition, the probability of setting off the source is defined as the hazard and the probability of reaction by the target is defined as the vulnerability (see Figure 1). The complexity of phenomena implies that risks are interlinked: from the successive interactions, each target may become the probable source of a new event. These sequences of events both occur through different temporalities, and in one or several territorial dimensions. Risk is thus a spatial and temporal concept. This approach of risks in a dynamic approach would partly explain the gaps between the extent and forms of disasters (what is observed) and the extent and forms of risks (what is probable) that we generally define with concentric buffer zones. In this conception of risk as a spatio-temporal process, it is

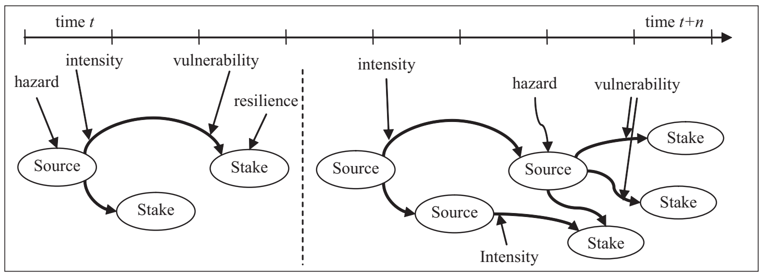

Fig. 1. Interactions between sources and stakes

fundamental to distinguish:

- Hazard, as the probability for a source to change its state in a qualitative and eventually quantitative way, at a time t. This change of state depends on the problem: for instance, in the case of an epidemic and at the individual level, it refers to the transition from a susceptible to an infected state;
- Intensity, as a measure of the quantity of energy released by a source (output), from its change of state and towards the outside. If the reference period of the study of intensity is relatively short, then we can comprehend it, not as a simple result, but as a process which describes the behaviour of energy in time and space. For example, the study of the diffusion of a toxic cloud after its release in the atmosphere;
- Vulnerability, as the probability for a stake to be disrupted by the energy released by a source, and thus to change its state (qualitatively or quantitatively). This probability is the result of a process which describes how the stake behaves to protect its entrances from the exits of the source, and the quantity of energy which gets into the stake. For example, the level of individual's sensitivity to panic behaviours which are displayed around him, and thus the probability for him to panic;

- Resilience, as a measure which describes the ability of the stake to adapt to change after a disturbance. For example, how individuals recover from a situation of individual, and eventually collective panic?

This last concept, richer than that of resistance already mentioned, was recently introduced in the literature. Some researchers have suggested, in order to reduce the damages of disasters and thus to minimize the vulnerability of exposed elements, to adopt a management strategy of risks based on this concept of resilience [4, 5, 6]. It can be defined as the ability of a system to return to a single steady or to a cyclic state after a perturbation. This concept can thus be useful to analyse the dynamic part of the system, especially its capacity to find new trajectories and rebound after a disturbance. Such a definition of risk gives the complexity of the objects considered: they may be successively sources and targets, and damages may have most of the time indirect origins with the first phenomena. In addition, according to the type of event, a same structure of interactions between a source and a stake may be a positive or negative part of vulnerability. The traffic network is a good example. If it is known to be a driving force for an epidemic hazard, it is however considered as useful for a fire hazard. Therefore, an analysis of network vulnerability in the field of risk studies is fundamental. In the case of panic phenomena, we find this same kind of complexity. In a situation of panic, the most vulnerable individuals to the intensity of the phenomenon (for example the diffusion of a toxic cloud) can quickly change their behaviours: from a state of non-panicking population to that of population in panic. If for the French school on the one hand, the terrified individuals are submitted to their gregarious instincts and irrational behaviours, for the American school on the other hand, the individuals keep forms of lucidity, abilities to analyse the situation and to take decisions: copying the neighbours, escaping... [7]. How irrational individuals may be or not, the non-linear interactions are very important in the diffusion of a panic. A few individuals may spread a panic among a whole group. The crowd as a whole can then become a source for other human and technological stakes. The self-organization theory is well adapted to give an account of the emergence of such phenomena for which little local disruptions may product global and unpredicted events. The self-organization theory identifies the principles which allow us to describe how a system creates his own behaviour at a global level, persisting in time and space, from the numerous interactions among entities displaying at one or several lower levels. These interactions are generally local ones, develop in the vicinity of each other, and such systems are characterized by the absence of planning: no global control which would pilot such structure, such behaviour, or such form. These kinds of systems are called "emergent systems" because their developments are not fully explained by the properties of entities at inferior levels. As most of natural or technical systems, self-organized systems are not systems whose equilibrium is permanent. Impermanence is the only reality of the living world. The activity of a system, dynamic and open to the outside like all the living systems, is in evolution. Self-organized systems arrange their behaviour in relation to certain points in their environments. Order in an interconnected system of element arises in the vicinity of attractors, which create and maintain patterns within the system. Evolution between attractors can be cyclic like prey-predator systems. Such systems are characterized by phases of intense activities: the curves of population linked to the two groups reversing more or less regularly along the time. Otherwise, the system can evolve towards a stationary state, converged on a point of attraction and absorbing progressively its activity. The activity of the system can lead it through different states through the time. This switch from a state to another is situated close to a point of bifurcation that may lead towards chaos. In an earlier work, we explored the different phases of activity of a system from the example of the logistic function often linked with diffusion processes [8, 9]. When the system evolves from a bifurcation threshold, the transition from one state to another qualitatively similar refers us to the concept of resilience. The stability of self-organized systems goes hand in hand with a possibility of change which explains that all living systems go through different phases during their activities. These phases are theorised by the criticality [1 op. cit.], which shows that all self-organized systems evolve towards a critical state and that a small and local disruption is sufficient to make the system change. This phase is characterized by a system which goes into a phase of mutual and global interaction during which the level of connections and interdependences of the elements of the system is maximal. If they are useful in a heuristic context, such concepts are however difficult to use when one wants to apply them or to spot them in an empirical way. How knowing if a particular system comes from a decentralised context or not? How qualifying, identifying the emergent phenomena in such systems? How evaluating the intensity of relationships between elements at the same level and between the elements at different levels? How measuring resilience in a system? From measures based on particular methodologies? Systemic measures? Indicators? These uncertainties lead us to propose simple models of the complexity. This way of modelling is based on a constructivist approach for which the principle of parsimony is the crucial point for scientists who wish to tame the "artificial creatures" they build.

3 Simulating panic phenomena: methodological orientations

The aim of the MOSAIIC project is to study individual behaviours and their consequences during an industrial accident, and mainly through an analysis of the traffic network vulnerability. The hypothesis of this project is that any traffic system, made of numerous mobile entities in mutual and environmental interactions, tends to evolve towards a critical state. A small fluctuation may thus disturb the system toward a phase which considerably increases the vulnerability of the persons if the origin of the disturbance, even indirect, is a technological or natural event. The experimentation in this field is of course either hardly conceivable or difficult to realise. Thus, the modelling methods and computer simulation offer an interesting option.

3.1 An environment of risk where hazard and vulnerability are statistically weak

According to Dauphine's classification of risks [2 op. cit.], our case study belongs to the category of local and short time events. The analysis of technological disasters is especially relevant today in a context of urban growth leading to a proximity between residential areas and industrial plants, and after recent industrial events (AZF in Toulouse, Mède in Marseille...). The gap between the dynamics of an observed disaster and the structure of the risk generally estimated in cities is partly explained by environmental factors. In urban areas, the variety and the number of sources and targets may grow in the course of the event. This fact is partly the result of the proximity of elements and of the growing interactions between them. However, the main characteristics of these environments for the individuals are both the quality of buildings to confine and the traffic network in order to escape and to be rescued. As a consequence, based on the conception of risk developed in 2.2, we view global risk as a measure of all the local and contextual risks that can be observed in a situation, and for which the sequence of interactions is determining for the magnitude of the risk and of the disaster. Thus, the source is an object partly submitted to hazard and probabilities, whose outputs are a quantity of energy released (virus, toxic cloud, individual aggressiveness, physical pressure...). This energy moves in space depending on the nature of the released energy. In order to counter the flows and to prevent the target stakes from being reached, preventive measures can be taken to limit the vulnerability upstream: alarms, buffer zones, educational measures etc. The aim is to reduce the inputs to the target objects (stakes). However, if the quantity of energy coming in the stakes is important, then these last may have a high probability to become targets. These last will then determine the outputs towards new stakes (see Figure 1). In this conception of global risk as a dynamic process in which the sequences of phenomena may be numerous, the MOSAIIC project proposes to focus on individual behaviours and on vulnerabilities linked to them. Thus in this project stakes and sources are humans.

3.2 The vulnerability of traffic networks during disasters

Studies dealing with vulnerability of systems need to take into account the constraints that both time and space present. The spatial level has to be defined. If a disaster may destroy a system, this last is - most of the time - a subsystem belonging to a bigger system which may not be disturbed by this disaster. Once the spatial level of the vulnerable system defined and analysed, elements and interactions of the system have to be recognized. In this paper, we will especially focus on the vulnerability of traffic networks in order to estimate its consequences on the exposed populations.

Self-organised and stable systems

The traffic networks may be directly or indirectly the origin of a disaster. For instance, the transport of dangerous materials in inner cities is a factor which tends to increase hazards. In this case, a mobile source (a truck) is not submitted to the same types of control and is not classified in the same category of risks as a static source (a factory). In addition, the nature and the quantity of stakes may vary during the shift of the object. An other aspect concerns the stakes and the vulnerability, and the need to qualify the role and to quantify the impact of traffic networks on a disaster. The urban environment is strongly restricted by its traffic network and may create use conflicts between the 'active' or 'passive' actors of the crisis. As one of the options to avoid epidemics is to isolate individuals [10], a sound management of technological disaster would propose to evacuate them out of a perimeter and then to confine them beyond a security line. However this strategy is rarely used and, in fact, is difficult to implement. Different individual strategies and behaviours coexist during an accident. We can summarize these strategies by considering two forces: a centrifugal one (moving away) and a centripetal one (moving closer) [11]. These two forces, constrained by the reticular environment which limits the possible paths may produce three types of movement or flows within the network: a flow in the opposite direction of the source, a flow towards the source, and a parallel one (the source is a front) or perpendicular one (the source is a point) to the source. According to the connectivity of the network[1] (see Figure 2) and the area where the event is located, the different types of mobility will be more or less possible in a given perimeter. How characterizing the "normal" regime of a network and how detecting the change of this regime toward an exceptional activity? This new regime could be considered as a precursory sign of dysfunctions in the system, and in our case of a possible disaster. The average regime observed in a traffic network can be written with a function A. It is an indicator of the level of the functioning of the system for a time t.

$$A_i = tmp_i - tp_i \tag{1}$$

where *tmpi* is the average traffic on the network at a time i and *tpi* is the instantaneous traffic on the same network. Within this framework, *tmp* correspond to a traffic modulation on different routes which are always the same in the network and at different moments in a day. The global *tmp*, as shown in

[1] we use the connectivity index β [12]which is based on non oriented graphs, and can be calculated by carrying over the number of nodes (s) to the number of links (l) : $\beta = l/s$

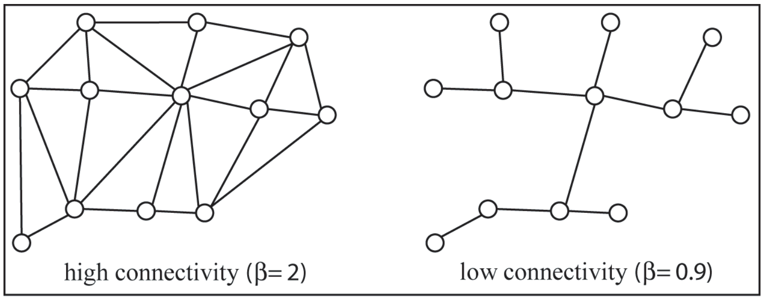

Fig. 2. Two graph models of a road network

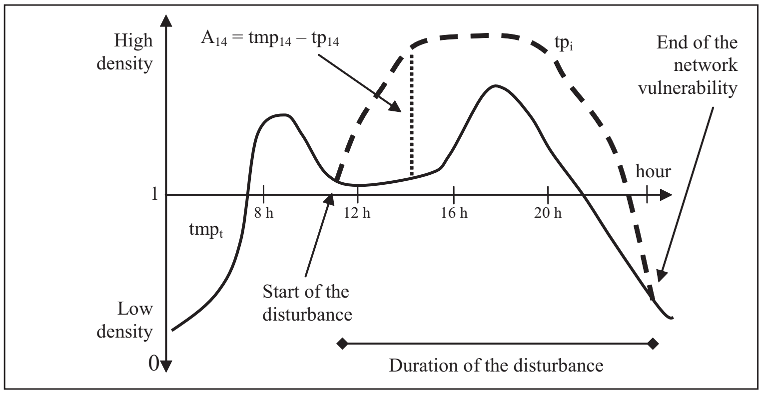

Fig. 3. Comparison between a diagram of disturbance and a series of daily average values

the Figure 3, is an average value at different hours of the day (continuous line on the graphic). For example, the *tmp* indicates the average value of density for a week day (for instance at 8am, in the graph from the southernmost point to the northernmost one) (see Figure 3). We can select a standard day to analyse the variability of situations, and thus to observe the consequences on the dynamic of a technological accident. Doing this way, we observe three very different types of daily modulations: the working days (JO), Saturday and the days before official holidays (SVF), Sunday and days before official holidays (DJF)[2]. This typology emphasizes the intervals between different days at the same hour. In addition, it allows us to compare the average hourly values between them in order to give a qualitative level of the functioning of the network: a level of fluidity, for example (horizontal continuous line on the graphic). At the same level of analysis, the *tpi* is the traffic observed on

[2] This parameter (C) is equal to the hourly trafic car average on an axes (VMH) divided by the daily trafic car average (VMJ), divided by 24. Thus, $C = VMH/(VMJ/24)$, this parameter has an average equal to 1.

the network, measured 'in live' during the simulation. So if the *tmp* is an estimation calculated from a counting during a period of time, then the *tpi* is the traffic in the network, or in a path, observed at a given moment. For example, the *tp*8 value indicates that at 8am on the 2nd of August, n vehicles are in the graph from the southernmost point to the northernmost one. As a consequence, if the *At* value is positive, the traffic on the section is, on average, higher at this hour and during this type of day, than the traffic recorded at the moment i. On the contrary, if *Ai* is negative, the traffic, observed at the moment i on the network, is higher than the average traffic. The advantage of such a formalization is to show, at which moment the system enters in a disrupted phase, the duration of this phase, its intensity and at which moment the system recovers its stable regime. Such a diagram presents our conception of the traffic network: a complex, stable and partly self-organised system whose dynamic is independent from the entities which constitute it. Although the entities (cars, pedestrians), may change, the laws which organise it remain. Yet, there is an autonomy of the traffic in relation to its constituent elements. The existence of dynamic independent patterns at a meso level of the network will lead us to model this dynamic at a meso level: for example with differential equations. But how switching from this modelling of the dynamic at a meso level to a modelling at a level where micro-changes have impacts on the global functioning?

Phases of criticalities

Why a system may move from a attraction point to another one and thus globally move away from the average observed traffic? Our hypothesis is that changes of aims and motivation within a group of individuals favour this bifurcation. These individual changes will be all the more quickly transmitted to the whole people (a total correlation between the elements of the system [1 op. cit.]) since they will be constrained by a network and a territory whose capacities of adaptation on a so short period is nearly non-existent. Only few entities have to change their behaviour to produce feedback effects on a part or on the whole system. Yet, its properties may be changed partly, temporally or on a long term basis. This criticality of the system is all the more high since we are situated, in the space of parameters, in a zone of instabilities which are characterised for example by a level close to congestion. The possibility for the system to bifurcate is all the more high since the degree of freedom of the entities in the system is weak, and since interdependence becomes global. In our case, that means that hazard and vulnerability factors are all the more important since the number of individuals circulating in the network and in the urban area is high. The diagram in Figure 4 presents these ideas. It combines the density (number of vehicles on an x axis) and the flow (number of vehicles along an y period of time). This diagram is in general estimated and observed on small intervals of space and time, in order not to combine different states of traffic. So the density is low if the individuals adopt the speeds of their choices only limited by statutory constraints. On the contrary, if both the density or the rate of occupation of the way rises, the traffic is more and more constrained and, beyond a certain limit - a critical density (Kc) - it reaches the congestion. We plan to model the micro level dynamics close to this threshold: for example, the variable of density will be converted into a list of agents on the relevant axes. In a next step, we will define the properties, methodologies, aims or strategies of these agents. The state of traffic thus

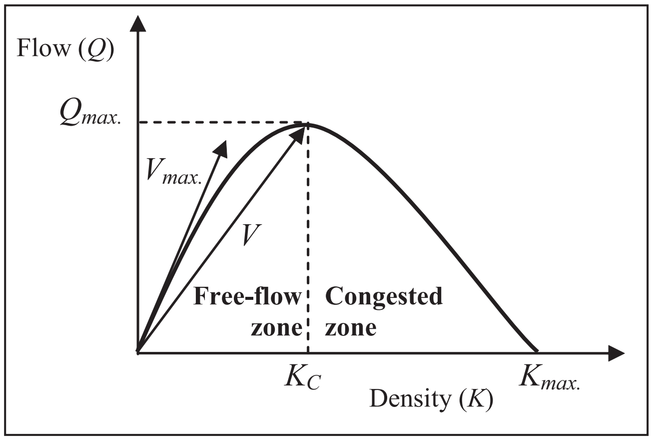

Fig. 4. Parabolic diagram: estimating congestion with flow and density

goes through different points, a possible trajectory leading to $Kmax$: points of attraction which indicate a full saturation of the road, or even of the network. The network resilience is thus the ability of the network to move to a point of attraction below the critical threshold Kc: a point that we plan to discover thanks to the analysis of the behaviour of the agents.

4 Conclusion

The analysis of the network vulnerability, measured by its trend to maintain a phase of global disturbance, proposes to stress one of the elements of complexity of disasters: the interactions between individuals and territory as well as between individuals and individuals. Despite this paper as well as the MOSAIIC project both focus on a particular category of risk, these reflections may lead us to suggest a more general model dealing with human behaviours in situations of crises. Thus, this model may be applied to other categories of risks that imply population shifts in strongly constrained spaces. Such a model offers an opportunity to test a great variety of behaviour scenarios as well as to analyse the incidence of the network structure on behaviours. Besides these different tests, we plan to study to which extent individual behaviours are likely to lead towards a critical point, even during situations when events occur far away from a critical phase. At last, this project plans to provide a cartography of the different strategies possible in contexts of crises to decision makers and people dealing with the problem of crisis management: evacuation strategies by getting closer to potentially disaster zones or strategies of intervention by mapping routes that allow to reach the targets.

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